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Manufacturing Concrete with Recycled Iron as a Partial Replacement of Fine Aggregate

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Abstract

Industrial waste iron can be a viable alternative construction material due to its sustainable environmental convenience. This paper presents the efficacy of the use of recycled iron powder (RIP) in manufacturing concrete. The focus of this study is to evaluate the physical, mechanical, and durability properties of concrete where RIP is used as a partial replacement of the fine aggregate. It was found that physical and durability properties such as fineness modulus, specific gravity, water absorption, and soundness of concrete improved by replacing 10, 20, 30, and 40% natural sand with RIP. The temperature of the fresh concrete gradually increased with an increased percentage of RIP mixing, but the workability decreased. The density of the RIP-modified concrete increased, and the porosity decreased with an increase in the percentage of RIP. After 7 and 28 days of curing, it was found that the compressive strength of the concrete was the highest (38.21 MPa) with 40% RIP, whereas the control mix (i.e., no RIP) had a compressive strength of 27.85 MPa. The findings of this study provide a better understanding of the use of RIP in producing new concrete.

Keywords
Recycled Iron Powder, Sustainability, Durability, Workability, and Statistical Analysis.

1. Introduction
Sustainable waste management is a worldwide concern nowadays. Most of the waste materials come from metals, plastics, and glass that need to be reused economically. Iron is a common metal waste that creates serious environmental problems, but it has a possibility of use as one of the components of concrete mix. The increasing amount of waste iron is one of the prime environmental issues in the present world. A huge amount of waste iron is generated from the industrial sector. This solid waste is considered a perilous material and poses potential environmental pollution threats. Some recent research and field demonstrations have shown that decent quality concrete with decent workability can be manufactured by using manufactured fine aggregates. The use of waste iron in its powder form as a partial replacement of sand in producing concrete or other civil engineering projects saves land space and reduces the need to extract natural raw materials.

1.1 Objectives
This study is part of a sustainable metal waste management initiative undertaken by a local municipal authority in Bangladesh. The primary objectives of this study are to have a better understanding of the use of recycled iron powder (RIP) in producing new concrete, manufacture concrete by using waste RIP as a partial replacement of sand, and assess the workability, strength, and durability properties of concrete manufactured with RIP.

2. Literature Review
Tayeh and Saffar (2020) investigated the utilization of waste iron in the construction sector. In this study, waste iron was reused as a partial replacement of fine aggregate in a mortar. They found that the increasing amount of iron powder decreased the compressive strength of mortar due to the higher amount of voids. On the other hand, a significant increase in flexural strength was observed with an increased amount of waste iron. The mortar specimens with 40% iron powder showed the highest flexural strength, which was 14.83% higher than that of the reference specimen. Another relevant study conducted by Ismail and Al-Hashmi (2008) reported that the concrete mixtures made with 20% waste iron had higher compressive strength and flexural strength compared to the concrete that was made with natural fine aggregate. They also evaluated other properties such as slump, fresh concrete density, and dry concrete density, of concrete modified with waste iron and reported favorable properties. Alzaed (2014) evaluated the compressive strength of 144 standard cube and cylinder samples of concrete modified with 0, 10, 20, and 30% of iron. They reported that the 28-day compressive strength gradually increased when iron powder was added to the concrete mix more than 10%.

Ghannam and Rosa (2016) conducted a study on the use of recycled granite powder and iron powder as a partial replacement of sand in concrete. This research pointed out that the partial use of these byproducts will reduce the consumption of sand in the construction sector thus preserving more natural resources. They prepared 20 cubes, 10 beams of concrete with iron powder, 20 cubes, and 10 beams of concrete with granite powder and performed compressive and flexural strength tests. It was observed that the replacement of up to 20% of sand by weight with iron powder increased compressive and flexural strength. The increase was more pronounced in flexural strength compared to compressive strength. This study also expressed that durability is essential for the proper use of these recycled materials in structural applications. Al-Jabri et al. (2009) investigated the effect of using copper slag as a replacement for sand on high-performance concrete. The results indicate that up to 50% of copper slag as sand replacement produced comparable strength. In addition, mixes with 80% and 100% copper slag replacement gave the lowest compressive strength, which was nearly 16% lower than the reference concrete.

The current study investigated the utilization of a large amount of iron waste in the form of RIP as a partial replacement of fine aggregate (natural sand) in concrete. As part of this study, standard cubes using different amounts of RIP in concrete mixtures were prepared and tested in the laboratory to elucidate their effects. Further, selected physical properties (e.g., temperature and slump) of fresh concrete, and mechanical properties (e.g., compressive strength) and durability properties (water absorption and porosity) of hardened concrete were carried out in the laboratory. The finding of this study has provided a groundwork for further research on the efficient applicability of RIP in producing concrete in Bangladesh.

3. Material Properties and Methods
The study included preparing concrete cubes with and without RIP as a replacement for sand. The concrete mixtures had a combination of natural sand and RIP (0, 10, 20, 30, and 40%) as fine aggregate, Portland composite cement as the binding material, crushed stone as coarse aggregate, and water.

3.1 Materials & Methods
Waste iron samples were obtained from a local industrial workshop. Natural sand used in this study was obtained from a local river bed, and it was free from any deleterious substances. Both sand and RIP were passed through a sieve opening of 4.75 mm. These fine aggregate was conformed to Indian Standard (IS): 383 and tests were carried out as per IS: 2386 (Parts I to V). The fineness modulus for natural sand was 2.545, and that for waste iron was 2.950. The fineness modulus values of both types of fine aggregate conformed to the requirement of not being less than 2.0 or greater than 3.5. A pictorial view of RIP used in this study is shown in Figure 1. The sieve analysis of the fine aggregates (natural sand and RIP) was conducted and the results were compared with the minimum and maximum values recommended in the IS 383 standard (Figure 2). It was observed that the gradations of both fine aggregates were within the specification limits of the IS 383 standard.

Figure 1. Recycled iron powder is used as fine aggregate in concrete.

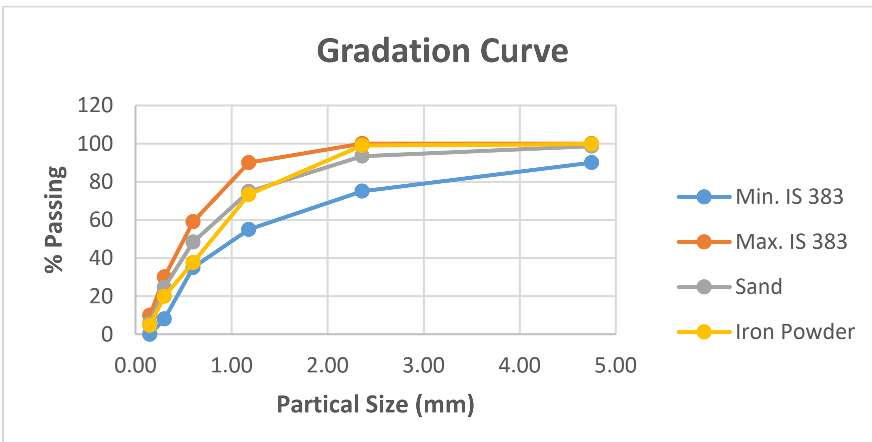

Figure 2. Gradation Curve of fine aggregate (sand and iron powder), comparison with IS 383 standard.

The following physical properties of natural sand (NS) and RIP were conducted: specific gravity and absorption per ASTM C 128, wash pass (finer than #200 sieve) per ASTM C 117, fineness modulus per IS: 383 & soundness (sodium sulfate) per IS: 2386. The evaluated physical properties of NS and RIP are presented in Table 1. It was observed that the percentage of passing finer than #200 sieve (P_{200}) for sand was 1.80% and that for RIP was 2.95%. The P_{200} value for RIP was more than that of sand, however, it was less than the allowable maximum value of 3% as per IS 383. On the other hand, the soundness (sodium sulfate) for sand was 1.072%, and that for RIP was 3.14%, which was significantly more than the former but was well below the maximum allowable amount of 10% per IS 383 and 2386.

Table 1. Physical properties of natural sand and recycled iron powder

Physical Properties	Natural Sand	Recycled Iron Powder	Codes & Standards
Specific Gravity	2.655	4.70	ASTM C 128
Water Absorption	2.06 %	2.82 %	ASTM C 128
Finer Than #200 Sieve	1.80 %	2.95 %	IS 383
Fineness Modulus	2.545	2.659	IS 383 & 2386
Soundness (Sodium Sulfate)	1.072	3.14	IS 383 & 2386

The nominal maximum size of the coarse aggregate was 20 mm. Sixty percent of the total coarse aggregate used in this study was 20 mm down, and the remaining 40% of it was smaller than 10mm. The physical properties of the coarse aggregate are presented in Table 2. Portland cement Type II was used in this study. The chemical and physical properties of the cement were carried out according to ASTM C 595 & IS 455, and they are presented in Tables 3 and 4.

Table 2. Physical properties of the coarse aggregate

Physical Properties	Result	Limit	Standards
Specific Gravity	2.777	---	ASTM C 128
Water Absorption	0.88%	---	ASTM C 128
Finer Than #200 Sieve	0.94%	Max. 3.0%	IS 383
Loss Angeles Abrasion	19.60%	Max. 50%	IS 383
Aggregate Crushing Value	16.96%	Max. 45%	IS 383
Clay Lumps	0.420%	Max. 1%	IS 383
Soundness (Sodium Sulfate)	1.121%	Max. 12%	IS 383

Table 3. Chemical properties of Portland cement

Test Parameter	Result	Limit	Standards
Magnesia as MgO	1.74%	Max. 6.0%	IS 455
Chloride Content	0.01%	≤0.1%	ASTM C 114
Sulfur as SO_3	1.85%	Max. 3.0%	ASTM C 150
Total Alkali (Na_2O + 0.658 K_2O)	0.50%	Max. 0.60%	IS 8112

Table 4. Physical properties of Portland cement

Test Parameter	Result	Limit	Standards
Fineness (m^2/kg)	385	Min. 225	IS 455
Soundness (Le-Chatelier)	0.50	Max. 10	IS 455
Initial setting time (minutes)	141	Min. 45	ASTM C 595
Final setting time (minutes)	255	Max. 420	ASTM C 595
7 days compressive strength (MPa)	21.54	Min. 20	ASTM C 595
28 days compressive strength (MPa)	36.15	Min. 25	ASTM C 595

3.2 Experimental Programs and Test Procedures

As mentioned earlier, five different percentage replacements (0, 10, 20, 30, and 40%) of natural sand by RIP were studied. Concrete cube samples were produced from different mixture proportions, as shown in Table 5. These mixture portions for concrete cubes contained a 0.43 water-cement ratio. Per British Standard (B.S.) 1881 (1952), the compression tests were conducted on 10 cubes (150 X 150 X 150 mm). Following Table 5 mixture proportions (i.e., mix IDs: RIP 0%, RIP 10%, RIP 20%, RIP 30%, and RIP 40%) all materials were mixed in a dry place, and uniform mixtures were ensured. The consistency of fresh concrete was measured by conducting a slump test to ensure the desired workability (75-150 mm) of the concrete (Figure 3 and Table 6). The temperature was also measured before preparing the cube samples. The measured slump values and recorded temperatures are shown in Table 6. The concrete cube samples were cast in three layers. Each layer of 50 mm was compacted until no air bubbles emerged from the surface of the concrete mold. They were then kept to dry at room temperature for 24 hours, removed from the molds, and marked, as shown in Figure 4. Afterward, the concrete samples were submerged under water until tested.

Table 5. Mixture proportion of concrete cubes

Mix ID	Sand (kg/m^3)	RIP (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)
RIP 0%	801.00	0.00	1094	159.10	370.00
RIP 10%	720.90	80.10	1094	159.10	370.00
RIP 20%	640.80	160.20	1094	159.10	370.00
RIP 30%	560.70	240.30	1094	159.10	370.00
RIP 40%	480.60	320.40	1094	159.10	370.00

(a) (b)

Figure 3. (a) Slump test for concrete with recycled iron powder and (b) temperature check.

Table 6. Workability and temperature of fresh concrete

Mix ID	RIP 0%	RIP 10%	RIP 20%	RIP 30%	RIP 40%
Slump Value (mm)	125	118	110	100	78
Temperature (°C)	26.1	26.6	26.7	27.9	28.6

(a) (b)

Figure 4. Test samples: (a) after compaction and (b) marked samples after roving from molds.

4. Results and Discussions

4.1 Density and Water Absorption

According to B.S. 1881 (1983), dry density and water absorption tests were conducted. The dry densities were determined after 3, 7, and 28 days of water curing when they were dabbled, and just before performing the compressive strength. An increasing trend of dry density was observed with respect to the curing time. For instance, in the case of

4% RIP, the dry densities after 3, 7, and 28 days of curing were 2561.19, 2568.89, and 2579.56 kg/m^3, respectively. Further, the dry density increased with an increase in the RIP content in concrete. To have a better understanding of the relative changes of dry densities after different curing days the percent increases compared to the reference mixture were estimated for all mixtures. Details of the increases in dry densities for all tested samples are shown in Figure 5. The water absorptions after 28 days of curing were also determined, and they were 6.58, 6.42, 6.28, 6.14, and 5.55% for 0, 10, 20, 30, and 40% RIP, respectively, compared to the control sample (no RIP).

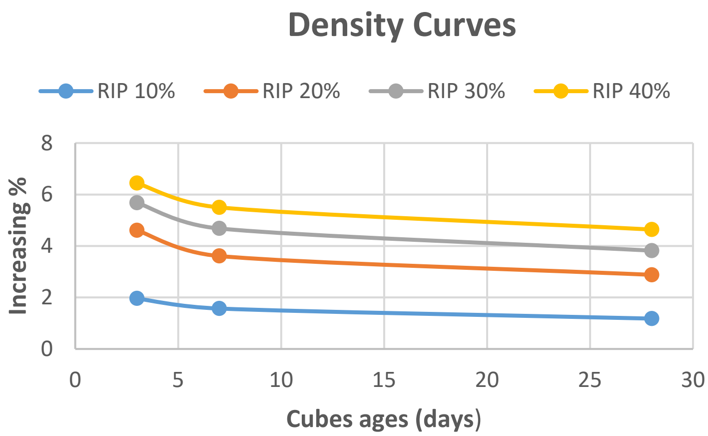

Figure 5. Increased dry density of concrete with different percentages of RIP.

4.2 Porosity

The porosity of concrete is an important parameter of assessment required for the design of reinforced concrete structural elements. Porosity is expressed as a percentage of the relationship of the volume of the open pores in the specimen to its exterior volume, as shown in Equation 1. Some physical and performance properties such as the composition of concrete, ease of casting in practice, time for maturing and hardening, rate of hydration and reactions, and risks at freezing are influenced by porosity. The influence of free water on the concrete behavior depends on both the amount and nature of porosity because water absorption in a concrete specimen is related to the presence of voids in it. The higher the volume of voids in concrete, the easier and faster chloride ions strew through the concrete.

$$\text{Porosity } \% = \frac{Total\ pore\ volume\ (Vp)}{Total\ bulk\ volume\ (Vt)} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

According to BS 1881: Part 122, it requires oven drying of concrete specimens at 105°C for 72 hours. After removing the cubes from the oven, they were allowed to cool at room temperature for 24 hours and the mass to a constant weight was determined (let's say, dry weight is D). Then the specimen was immersed in water for 30 min. at a depth such that there was 25mm of water over the top of the cubes. Then the saturated surface dry weight (W) of the cube was determined after taking the specimen from the curing tank and removing the surface water with a towel. The total pore volume was determined by subtracting dry weight from saturated weight. It was assumed that 1 cm³ of water weighed 1 g at a room temperature of 25ºC.

In this study, the apparent porosity values of concrete made with 0%, 10%, 20%, 30%, and 40% RIP were 15.23%, 15.05%, 14.99%, 14.81% and 13.57%, respectively, at 28 days (Figure 6). The minimum porosity decrease was observed for concrete with 40% RIP. Such a decreasing trend of porosity with an increase in the RIP content is consistent with the mechanical strength, which will be elaborated on later in this paper. Water absorption or porosity of concrete is directly related to the durability of concrete. Interconnected porosity significantly influences the water permeability, while the open porosity and water-cement ratio are together the key factors prevailing the concrete strength. When open porosity increases, the concrete strength gradually decreases. On the other hand, the strength decreases with the water-cement ratio either decreases or increases from the optimum. The increase in water permeability often leads to a decrease in strength. As illustrated earlier, the porosity is expressed as a percentage of the relationship of the volume of the open pores in the specimen to its exterior volume. The higher the volume of voids in concrete, the easier and faster chloride ions strew through the concrete consistent with mechanical strength.

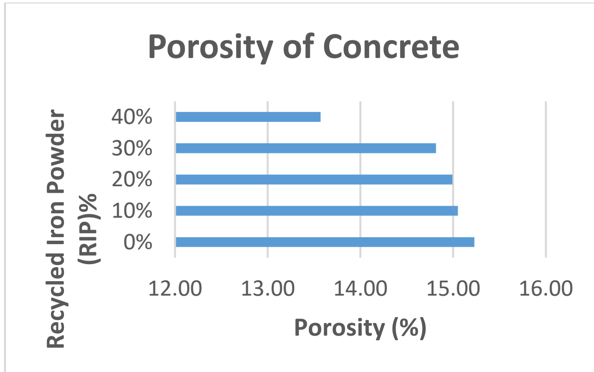

Figure 6. Porosity of concrete made with RIP.

4.3 Compressive Strength

Compressive strength was measured per BS 1881-116:1983. According to this standard, the surface of a specimen is cleaned and the dimensions of each specimen are checked that will be horizontal when it is tested. The surfaces of the testing machine are cleaned. Other objects are removed that have any possibility to come with contact between the cubes and the machine platens. Any packing between them is not used here. Now the cubes were placed carefully on the lower plate and then the load was applied from two opposite cast faces of the cube (Figure 7). The load is applied and increased incessantly without any shoving within a rate range of 0.2 N/ (mm^2s) to 0.4 N/ (mm^2s) until any greater load is sustained. The maximum load is recorded that is applied on the cube. In this study, the size of a cube was 150mmX150mmX150mm, thus the loading surface area of a cube was 22500 mm^2.

(a) (b)

Figure 7. Compressive strength: (a) loading time on the cube, and (b) after applied maximum load.

After 7 and 28 days of curing, compressive strength tests are conducted on the cubes made with 0%, 10%, 20%, 30%, and 40% RIP replaced with sand. Here the mix proportion 0% RIP was considered as the reference cube for this experiment. The compression testing machine used in this study had a capacity of 2000N, model: IFANTIDIS, ID: RFP-03. Before conducting the test, the compression machine was calibrated by a certified technician.

The compressive test was performed at 7 and 28 days of curing of the cubes. The 7-day compressive strengths of concrete with 0%, 10%, 20%, 30%, and 40% RIP were 23.55, 24.79, 24.85, 26.02, and 27.85MPa, respectively. And after 28 days of curing, the compressive strengths of these samples were 33.96, 34.34, 34.53, 37.22, and 38.21 MPa, respectively. It was observed that compressive strength for 10% and 20% RIP replaced for sand in concrete almost nearly the same and after that a significant change was observed at 30% and 40% RIP mixed concrete. It was the result of a high percentage of iron powder in concrete. This high strength of concrete can be linked to the higher strength of RIP compared to local sand. The iron powder has a rough surface, angular shape, and high mechanical properties that may have provided the structure of a stronger interfacial transition gyre between the cement and aggregate. Furthermore, Figure 8 represents comparative compressive strengths between 7 and 28 days of cured samples.

Compared to the reference cube (0% RIP), after 7 days of curing, the increasing ratio of compressive strengths of 10%, 20%, 30%, and 40% RIP samples were 5.28%, 5.50%, 10.48%, and 18.23%, respectively. Similarly, after 28 days of curing, the related increases in compressive strength of these samples were 1.12%, 1.68%, 9.60%, and 12.53%, respectively. Further, It was observed that for 10% and 20% RIP, the compressive strength increasing ratio was about the same magnitude, and a remarkable change was noticed at 30% and 40% RIP mixed concrete. The maximum strength was observed for 40% RIP mixed concrete. Thus, based on the compressive strength and porosity data, a 40% RIP is considered to be the optimum replacement level of natural sand.

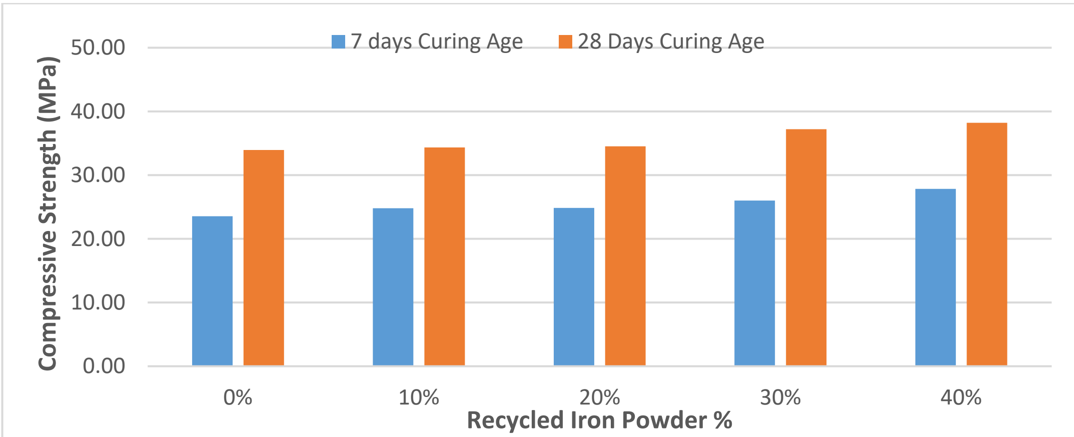

Figure 8. Compressive strength ratio after 7 and 28 days of curing age.

4.4 Durability of Concrete

A durable concrete ensures a better longevity of the structure as a whole. High concentration of chloride ions has a detrimental effect on the durability of concrete. The lower the chloride permeability, the better the durability of concrete. Water absorption and porosity tests were done to know the durability of the concrete cube (150 X 150 X 150 mm) mixed with 0%, 10%, 20%, 30%, and 40% RIP. Results are presented in Table 7.

Table 7. Durability of concrete (water absorption and porosity test)

Parameters	RIP 0%	RIP 10%	RIP 20%	RIP 30%	RIP 40%
Cube Weight after 28 days Curing (SSD) (gm)	8320	8418	8560	8638	8706
Dry Weight of Cube (gm)	7806	7910	8054	8138	8248
Water Absorption (%)	6.58	6.42	6.28	6.14	5.55
Porosity (%)	15.23	15.05	14.99	14.81	13.57

4.5 Discussions

The statistical data analysis ANOVA (Analysis of Variance) is conducted to present the compressive strength of concrete mixed with different percentages of RIP. It is found that the p-values of (0% RIP vs 10%RIP), (0% RIP vs 20% RIP), (0% RIP vs 30% RIP), and (0% RIP vs 40% RIP), are greater than the significance level (alpha level selected 0.05). It means that all the groups have more than a 5% chance of belonging to the same result of compressive strength. Compared to the reference mixture (0% RIP) all other mixtures have significantly increasing mean value and the maximum mean value observed was 32.64 MPa for 40% RIP where 28.41 MPa was for 0% RIP mixed concrete. The tensile strength and flexural strength of the concrete prepared with RIP also have a significant increase compared to the reference concrete (0% RIP). Ubeid et al. (2020) have used some equations for obtaining the tensile and flexural strength of concrete mixed with waste glass powder from compressive strength results. According to ACI 318 (2002), the tensile strength depends on compressive strength, in compliance with Equation 2.

$$fct \quad = 0.56\sqrt{f'c} \quad \text{.......} \quad (2)$$

Where, t : Tensile Strength in [MPa]; and $f'c$: Specified compressive strength of concrete in [MPa].

Following Equation (2), the corresponding tensile strength after 28 days of curing are 3.24, 3.26, 3.27, 3.39, and 3.44 MPa for concrete prepared with 0, 10, 20, 30, and 40% RIP, respectively. And the maximum tensile strength was observed for concrete with 40% RIP.

According to ACI 318, flexural strength is also obtained by using Equation 3.

$$fcl \quad = 0.62\sqrt{f'c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, l : Flexural Strength in [MPa]; and $f'c$: Specified compressive strength of concrete in [MPa].

Following equation (3) obtained flexural strength from compressive strength results 28 days curing are, 3.59 MPa, 3.61 MPa, 3.62 MPa, 3.76 MPa, 3.80 MPa, respectively for 0% RIP, 10% RIP, 20% RIP, 30% RIP, 40% RIP mixed with concrete. Where the maximum flexural strength was found for concrete with a 40% RIP.

5. Conclusions

In this research work, the effect of recycled iron powder (RIP) as a partial replacement of local natural sand in concrete was investigated to determine the compressive strength and other physical and mechanical properties. Five different percentages of RIP were used in the concrete mixture to evaluate their effects on workability and performance properties. From the existing literature in public domains and the test results of the current study, the following conclusions can be drawn:

The temperature of fresh concrete gradually increases with an increase in the percentage of RIP. The maximum temperature of 28.6°C was measured for fresh concrete with 40% RIP.
The workability of concrete decreased with the increasing percentage of RIP because of its high angular and rough surface. The slump value of the reference concrete (0% RIP) was 125mm, which decreased to 78mm when 40% RIP was used.
A maximum dry density of 2579.56 kg/m^3 was observed for 40% RIP concrete after 28 days of curing due to the presence of a maximum percentage of heavy aggregate.

The water absorption decreased with an increase of RIP; a minimum water absorption of 6.14% was obtained for 40% RIP concrete.
A minimum porosity of 13.57% was observed for 40% RIP concrete.
The compressive strength increased with an increase in the RIP content. The maximum compressive strength 38.21MPa was measured for 40% RIP concrete after 28 days of curing age, which is 12.53% higher than that of the reference concrete cube (0% RIP).

The tensile strength and flexural strength of concrete also increased with an increase in the RIP content. Maximum tensile and flexural strength 3.44 MPa and 3.80 MPa, respectively, were calculated for 40% RIP concrete.

In summary, based on laboratory test results and analysis, RIP can be used as a replacement for natural sand and a 40% RIP is recommended to be the optimum replacement level for natural sand. This research work will be motivational for reusing waste iron as fine aggregate in concrete construction, and RIP would be a great sustainable waste management practice in the present industrial world.

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Biographies

Md. Al-Amin is a QA/QC Engineer of China Civil Engineering Construction Corporation (CCECC Bangladesh) and a graduate student of Rajshahi University of Engineering & Technology (RUET), Bangladesh. Have working experience in Nuclear Power Plant, Railway Earthworks & Railway Station construction, and Airport Runway Asphalt overlay projects contributing as Management, Planning, QS, and QA/QC Manager. Received Star Employee Award 2023 from current Company CCECC. Attained Tran-SET Summit-2023 hosted by Arkansas State University, USA, and in 3rd "24 Hours of Concrete Knowledge 2023," hosted by ACI. Present paper in Tran SET conference 2022 held in Austin, Texas, and published by ASCE.

Zahid Hossain is a Professor of Civil Engineering and Director of Graduate Programs in Engineering at Arkansas State University with a demonstrated history of working in higher education institutes and private industries. Dr. Hossain is skilled in experimentation, mentoring, lecturing, modeling, student development, and professional service. Received research funds from agencies such as the National Science Foundation, and the US Department of Transportation. Dr. Hossain has published over 100 peer-reviewed technical articles in professional journals and conferences. He served on different local, state, national, and international scientific committees and technical forums as Chair, Member, Lead Editor, Associate Editor, and Reviewer. Dr. Hossain is a recipient of multiple awards including the 2019 Faculty Award for Advising, the 2014 Faculty Award for Scholarship, and the 2014 Faculty Award from Oakridge Associated National Universities.